# Physics Benchmarks with the VELO Pixel Upgrade

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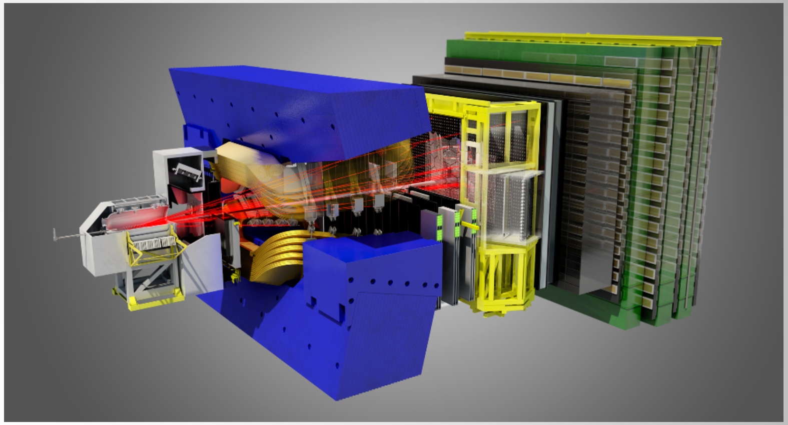
Outline

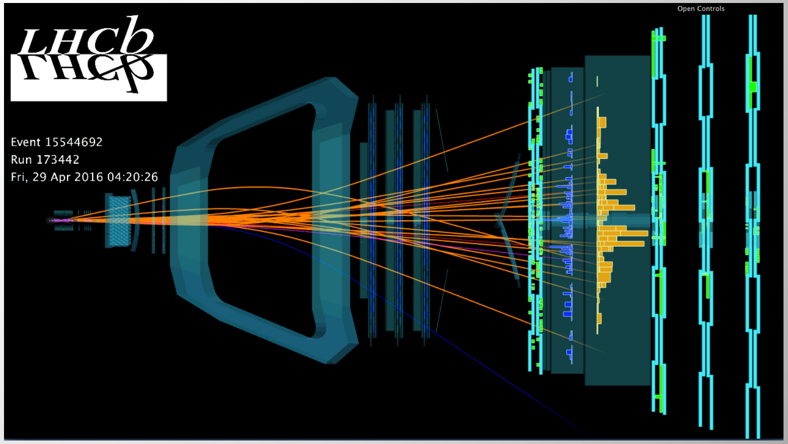
- The role of VELO in LHCb
- Performance for the VELO upgrade
    - Tracking
    - PV, IP resolution
    - Decay time resolution
- Plans beyond the current upgrade

University of Glasgow

# LHCb and its physics programme

- The original physics tag-line
  - CP-violation in and rare decays of b and c hadrons
- Programme expanded over time
  - Spectroscopy, EW, top, semi-leptonic, heavy ion, CEP, …
- Evolution towards the upgrade
  - Precision physics in the forward region
  - Software trigger at 40 MHz
  - Increased luminosity
- Benchmarks presented here taken from the b-physics programme
  - Much of this applies across the whole programme






**Non-referenced plots are from the VELO Upgrade TDR**

# LHCb: experimental environment

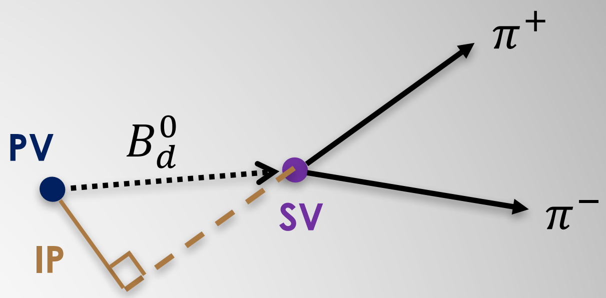
- Very large $b\bar{b}$ cross section in the detector acceptance
  - Estimated yields at full integrated upgrade luminosity (14 TeV)

| | $\sigma_{b\bar{b}}$ | $\int \mathcal{L}$ | # $b\bar{b}$ pairs |
|---|---|---|---|
| LHCb | 220 μb | $50\ \mathrm{fb}^{-1}$ | $11 * 10^{12}$ |
| Belle II | 1.2 nb | $50\ \mathrm{ab}^{-1}$ | $60 * 10^{9}$ |

- However: total cross-section ~100 mb
  - Average #interactions / crossing ~ 5 ($\langle\mu\rangle$ = 5.2 used in plots shown here)
  - 1/60 crossing contains a b-hadron
  - Belle II: fully reconstructed, clean events
- Experimental challenges
  - Trigger on & select signal candidates
  - Precision measurements
    - Despite the high track multiplicity

⇒ **Relies on excellent VELO performance**

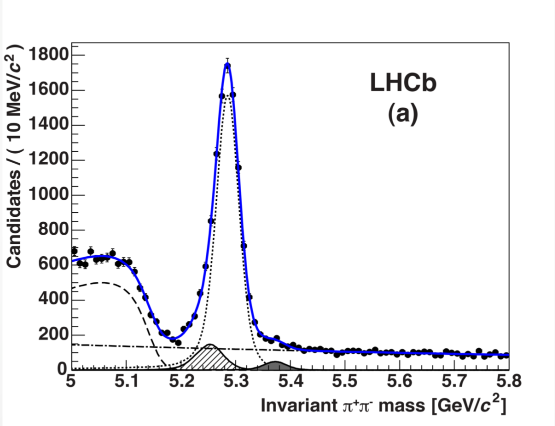
# Example measurement: CPV in $B_d^0 \to \pi^+\pi^-$

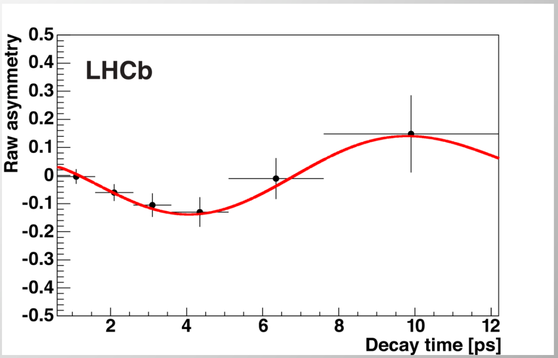



VELO in the analysis flow

- Reconstruction
  - Track and primary vertex reconstruction (PV)
- Trigger & Selection
  - Impact Parameter (IP)
  - Distance of closest approach (DOCA), secondary vertex (SV) reconstruction
  - Pointing variables & IP of the mother
  - Track & vertex quality
  - Flight distance & decay time
- Measurement
  - Some variable vs. decay time e.g.

$$\mathcal{A}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)}$$

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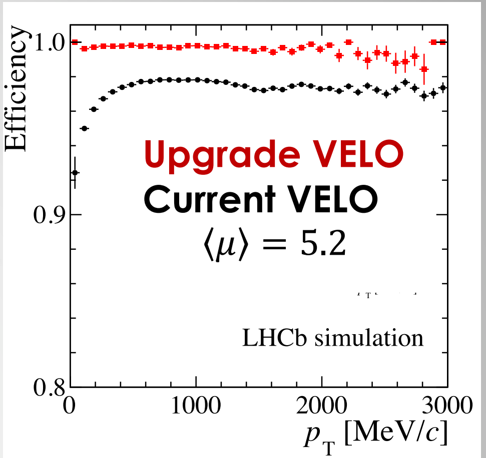
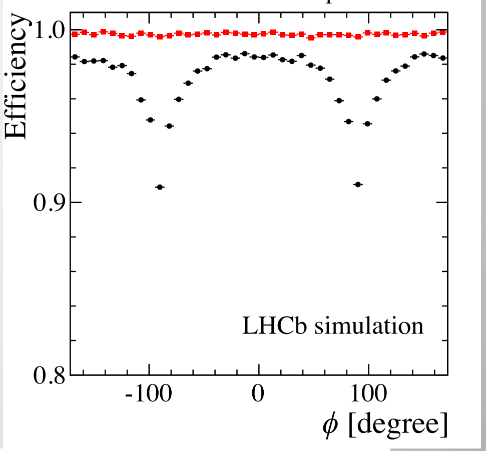
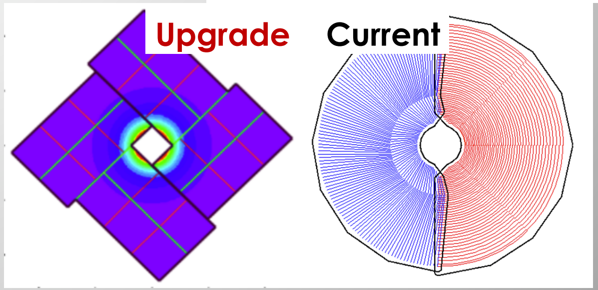
# Track reconstruction

- Software trigger at 40 MHz event rate
  - Fast track reconstruction possible with pixels
- Tracking efficiency remains high
  - > 99% for b-hadron daughter tracks
  - > 98% for current VELO on 2011 data
  - Not possible to run current VELO in upgrade conditions
- More uniform efficiency with pixel
  - Square pixels give more uniform efficiency than current $R\Phi$ geometry
    - More on this later
  - L-shape give a more uniform efficiency in $\Phi$
  - Material budget show similar structure in $\Phi$
    - Overlap regions smeared out in $\Phi$



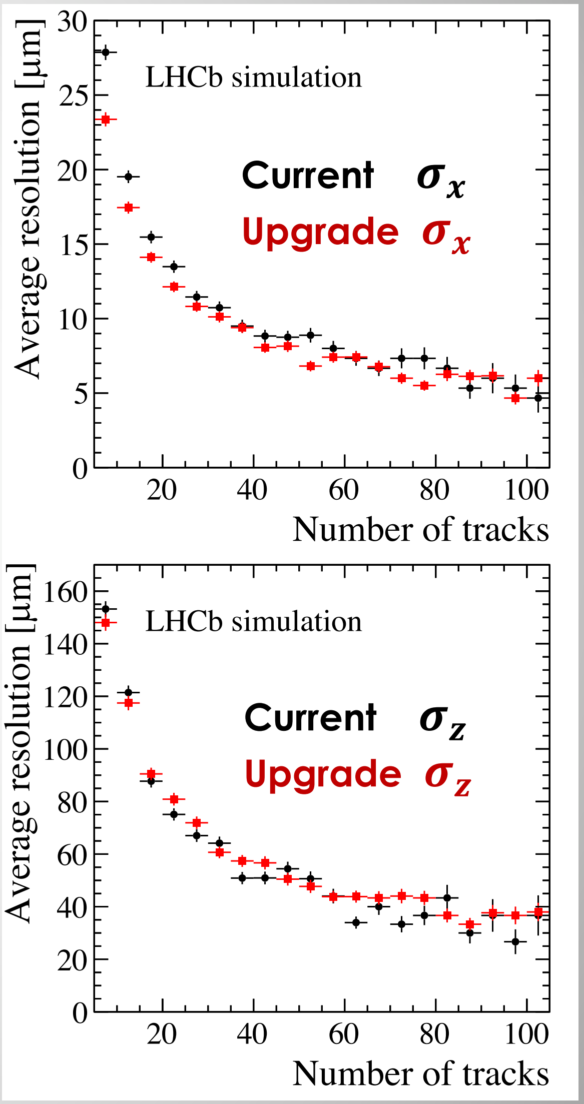
# Primary Vertex (PV) resolution

- PV resolution depends on # tracks
  - Min bias: <tracks/PV> ~ 55
  - B-hadron PVs: <tracks/PV> ~ 120

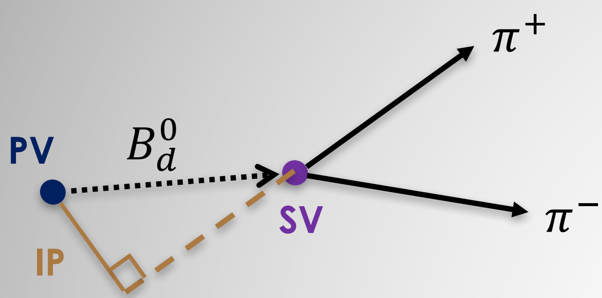
$$\sigma_x \sim 5\ \mu m$$
$$\sigma_z \sim 40\ \mu m$$

- PV resolution negligible contribution to uncertainty on other related quantities

- However: primary and secondary vertex association is important
  - Depends on pile-up
  - More on this later



# Impact Parameter (IP) resolution

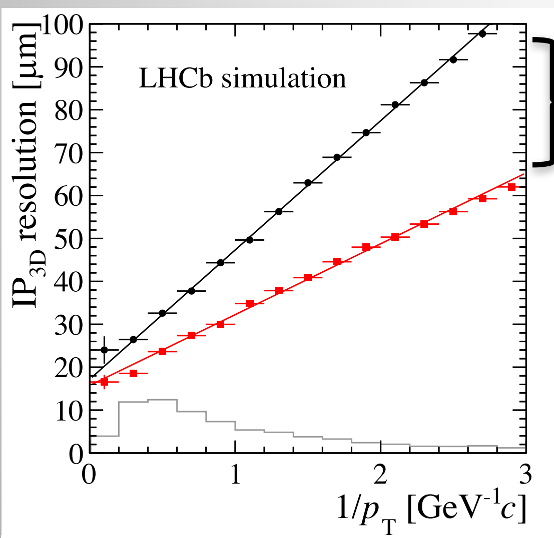



## Model of the IP resolution vs. $p_T$*

Radius of first measured point

Radiation length before second measured point

$$
\begin{aligned}
\sigma_{IP}^2 &= \frac{r_1^2}{p_T^2}\left(0.0136\ \mathrm{GeV}/c\ \sqrt{\frac{x}{X_0}}\left(1+0.038\ \ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2+\Delta_{01}^2\sigma_2^2}{\Delta_{12}^2} \\
&= \sigma_{MS}^2 + \sigma_{extrap}^2 .
\end{aligned}
$$




**Upgrade and current VELO**

$\langle\mu\rangle = 5.2$

## Multiple scattering (slope) term

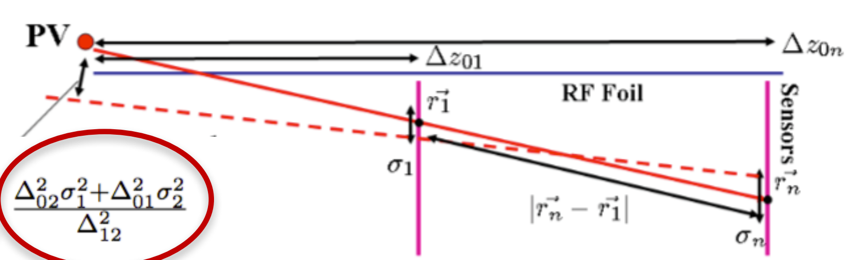
- Dominates at low $p_T$
- Significant improvement w.r.t. current VELO
  - Reduced minimum radius: 8.2 mm $\longrightarrow$ 5.1 mm
  - Reduced material budget
- Signal tracks typically $p_T$ > 1 GeV/c
  - Background rejection



*Full derivation in thesis by M. Alexander

# Impact Parameter (IP) resolution

## Model of the IP resolution vs. $p_T$



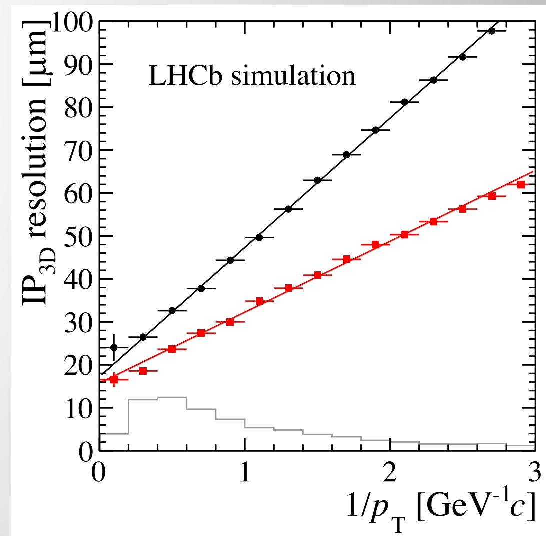

$$\sigma_{\rm IP}^2 = \frac{r_1^2}{{p_{\rm T}}^2}\left(0.0136\ \ {\rm GeV}/c\ \sqrt{\frac{x}{X_0}}\left(1+0.038\ \ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2+\Delta_{01}^2\sigma_2^2}{\Delta_{12}^2}$$

$$= \sigma_{\rm MS}^2 + \sigma_{\rm extrap}^2 .$$

$\Delta_{ij}^2$: distance between PV (0), first and second measured point (1, 2)
$\sigma_i^2$: hit resolution for the first or second measured point (1, 2)

## Constant term

- Dominates at high-pT
- Similar performance as current VELO
  - Reduced minimum radius: 8.2 mm ⟶ 5.1 mm
  - Increased inner pitch: 40 μm ⟶ 55μm
- Important for signal tracks
  - Distance of closest approach (DOCA)
  - Secondary vertex (SV) resolution

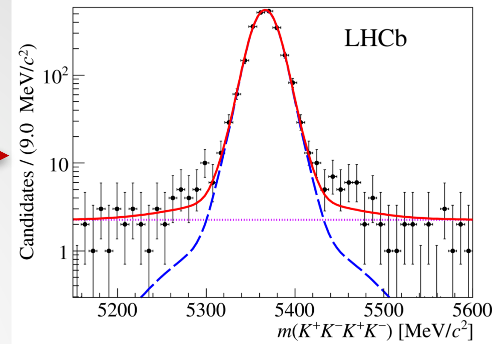



**Upgraded and current VELO**
$\langle\mu\rangle = 5.2$

# Secondary Vertex (SV) resolution

Where does SV resolution matter?

- Permits selection of very clean signal peaks, e.g. $B_s^0 \to \Phi\Phi$
  - Improved resolution gives diminishing returns

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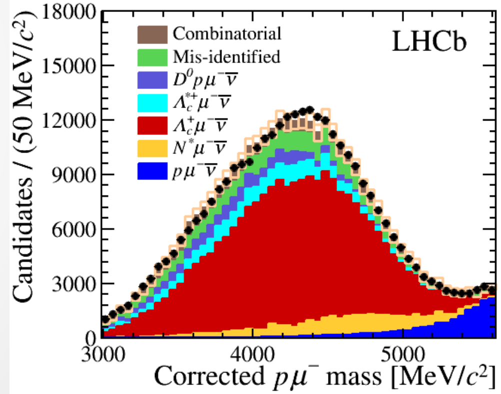
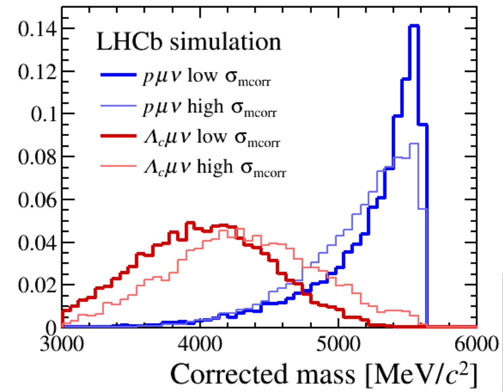
- Very different for semi-leptonic decays e.g.

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{\mathrm{FF}}$$

  - Challenging to reconstruct & select
  - Improved resolution would give significant increased signal/background

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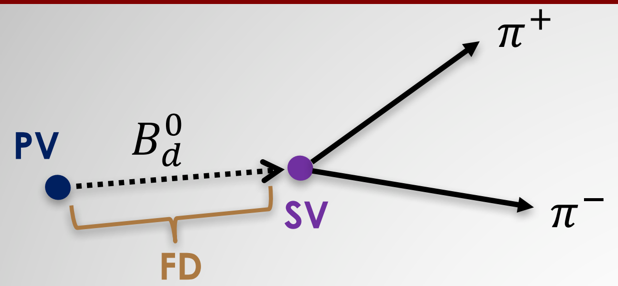
- Similar situation for $B_s^0 \to \tau^+\tau^-$
  - Sensitivity $10^6$ times worse than $B_s^0 \to \mu^+\mu^-$

# Decay time resolution



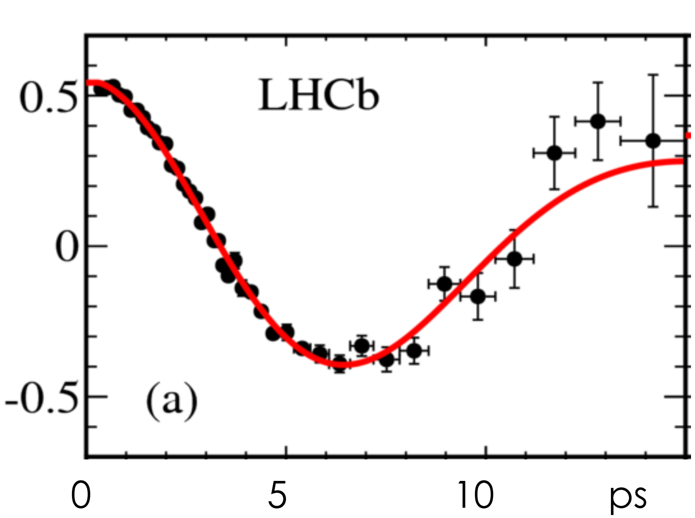

- Flight distance (FD) measured by VELO
  - Momentum and mass measured by tracking system

$$t = \frac{m \cdot FD}{p}$$

- Lifetime measurements: decay time resolution matters if $\sigma_t \sim \tau$
- Decay time resolution important for oscillation measurements
  - Works as a statistical dilution factor

$$D = e^{-\frac{\Delta m^2 \sigma_t^2}{2}}$$

Oscillations in $B_d^0 \to D^- \mu^+ \nu_\mu X$: $\Delta m_d = 0.505$ ps$^{-1}$

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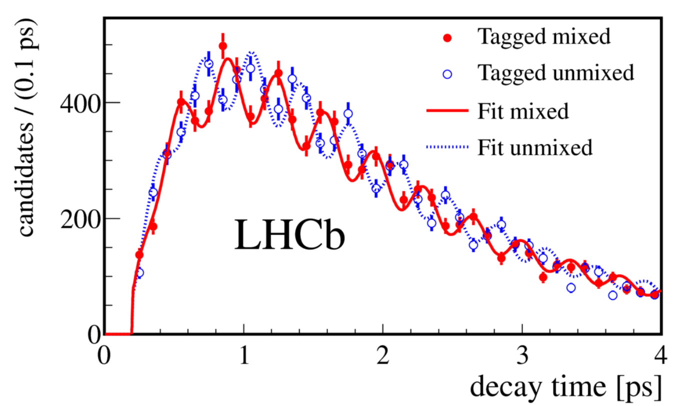
Oscillations in $B_s^0 \to D_s^- \pi$: $\Delta m_s = 17.8$ ps$^{-1}$

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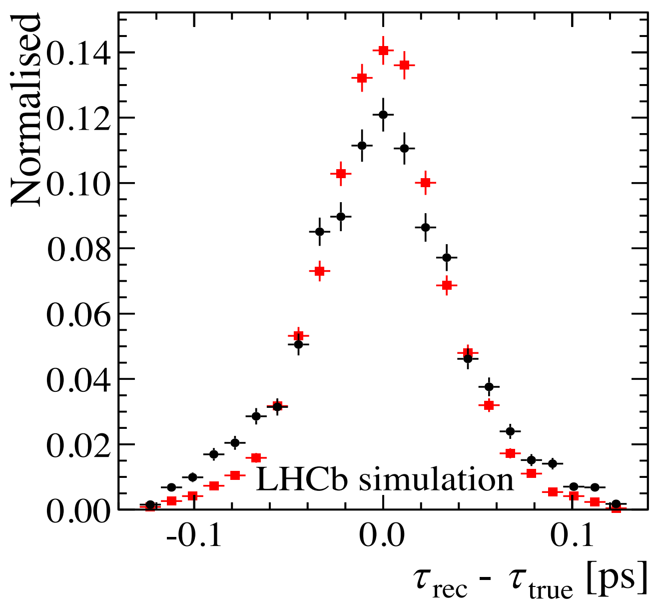
# Decay time resolution




Decay time resolution $B_s^0 \to \Phi\Phi$
Current VELO: $\sigma_t = 48.3$ fs
Upgrade VELO: $\sigma_t = 43.4$ fs

Cf. $\sigma_t \approx 50$ fs on 2011 data
(similar decay: $B_s^0 \to {}^{J}/_{\Psi}\,\Phi$)

- B-hadron and charm meson lifetimes: $\tau \sim 0.4 - 1.5$ ps
  - Resolution not an issue
- Charm baryon lifetimes: it starts to matter

$$\tau_{\Lambda_c^+} \approx 200 \text{ fs}$$
$$\tau_{\Xi_c^0} \approx 110 \text{ fs}$$
$$\tau_{\Omega_c^0} \approx 70 \text{ fs}$$

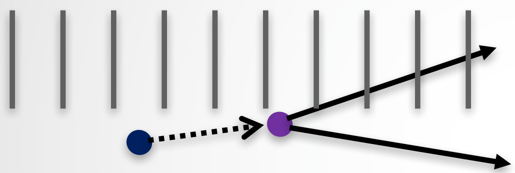
  - Doubly-heavy baryons even more so!
- $B_d^0$ oscillations: $\Delta m_d = 0.505$ ps$^{-1}$
  - Dilution factor = 1
- $B_s^0$ oscillations: $\Delta m_s = 17.8$ ps$^{-1}$
  - $B_s^0 \to \Phi\Phi$, current VELO $\sigma_t = 48.3$ ps
    - Dilution factor D = 0.69
  - $B_s^0 \to \Phi\Phi$, upgraded VELO $\sigma_t = 43.4$ ps
    - Dilution factor D = 0.74

**Dilution factor** $D = e^{-\frac{\Delta m^2 \sigma_t^2}{2}}$

**Difference corresponds to a 15% increase in effective signal yield**

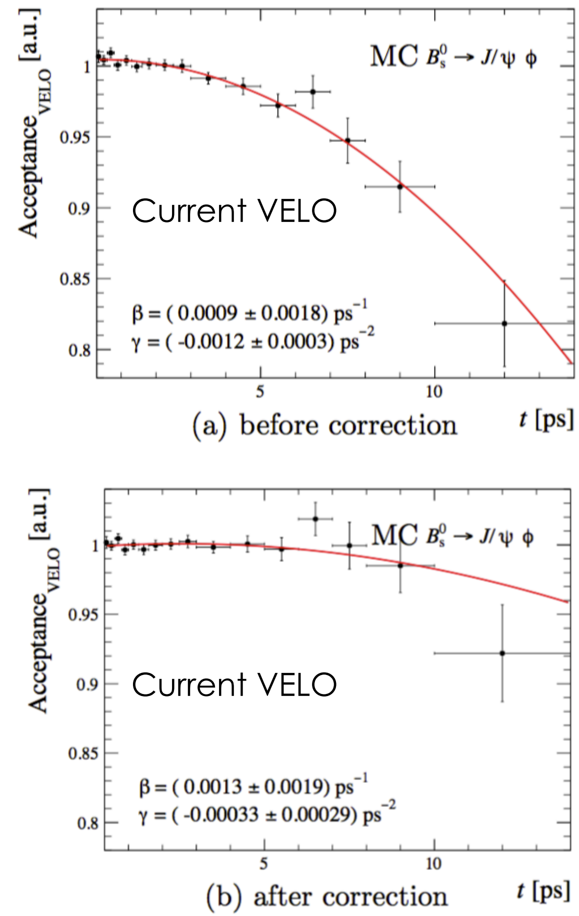
# Non-uniform reconstruction efficiency

- Reconstruction efficiency varies, e.g. as a function of decay time
- Upper decay time acceptance in current VELO
  - Long flight distance in z: run out of VELO stations



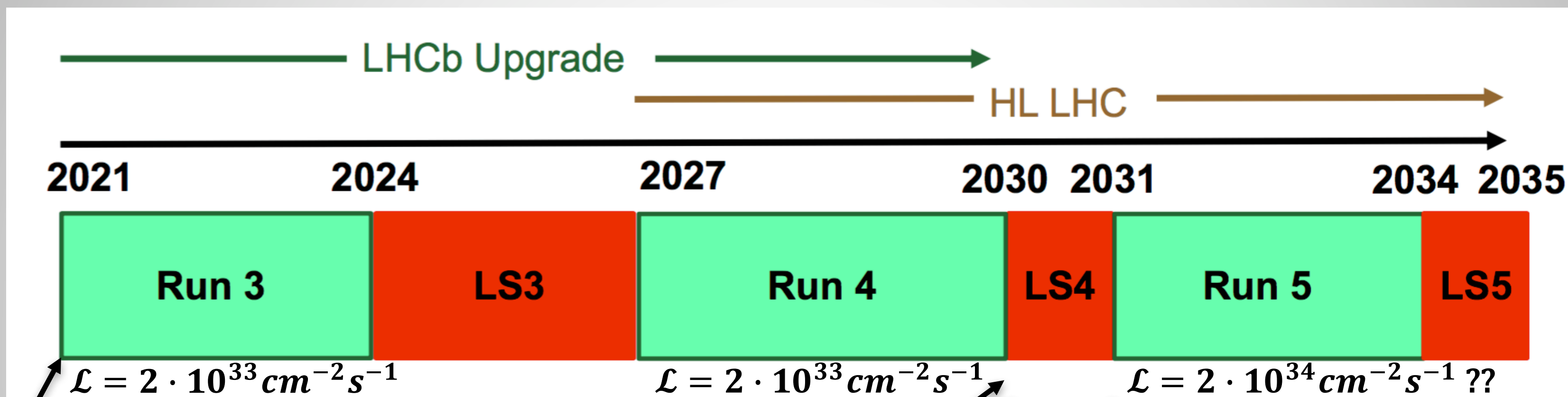
  - Long radial flight distance
    - $R\Phi$ geometry and pattern recognition algorithm disfavours tracks not originating from the z-axis
- Modelled and corrected for in analyses
  - Labour intensive process
  - Remainder: systematic uncertainty
- Pixel geometry less susceptible to this effect
  - But it is important to consider potential systematics already at the design stage

Reconstruction acceptance




Plots from thesis by F. Dordei

# Beyond the current LHCb upgrade




Start data taking LHCb upgrade

Nominal 50 $fb^{-1}$ collected

Phase-Ib upgrade:

- Minor upgrades & consolidation
- Nothing foreseen for VELO

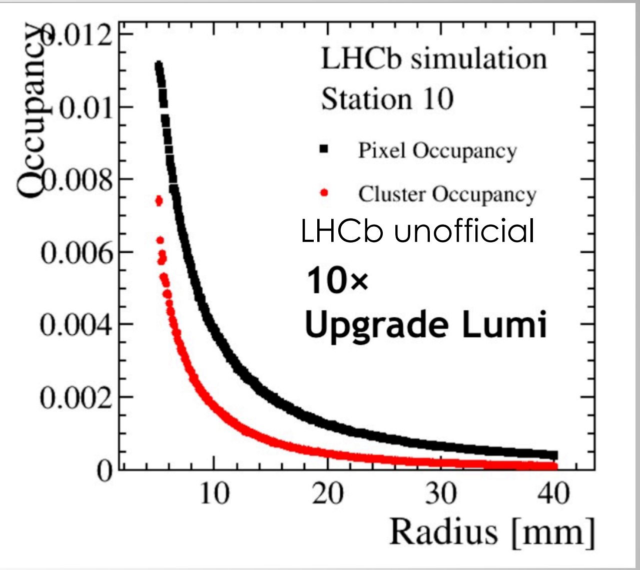
Phase-II upgrade:

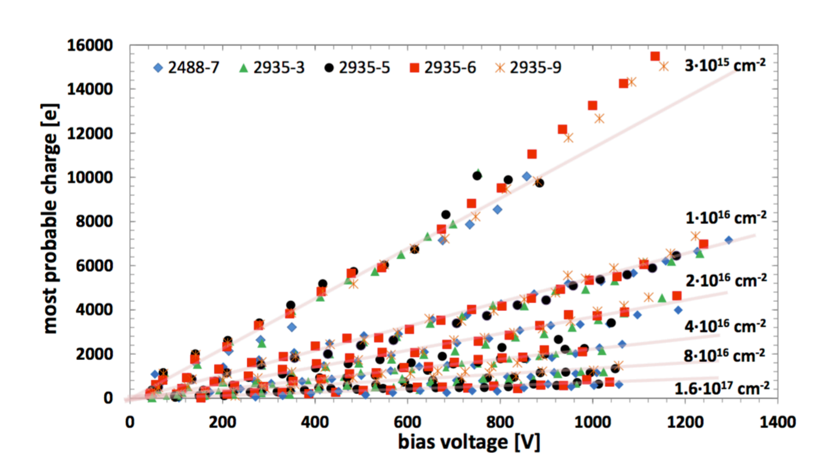
- Significant increase in luminosity
- Physics case under study
- Major detector upgrade
- Challenging and exciting prospects for VELO

Target: $\int \mathcal{L} = 300\ \mathrm{fb}^{-1}$

# Challenges for the VELO Phase-II upgrade

- 6x integrated luminosity – 6x radiation damage
  - Current upgrade: $8\times10^{15}$ 1 MeV $n_{eq}$ maximum
    - Is $5\times10^{16}$ 1 MeV $n_{eq}$ feasible?
    - Conventional sensors or new technologies?
  - Conservative: move away from the beam
    - $R_{min}$ = 12.5 mm gives same dose
    - Resolution degrades
- 10x luminosity – 10x data rates
  - VeloPix has 4 x 5.12 Gbit/s links for hottest ASIC
    - On-chip data transport
    - Increase the serial link speed?
    - Move O/E transition to hybrid?
  - Conservative fall-back
    - Move away from the beam
- Even higher multiplicity environment
  - Pattern recognition, IP resolution, …
  - Resolution remains crucial

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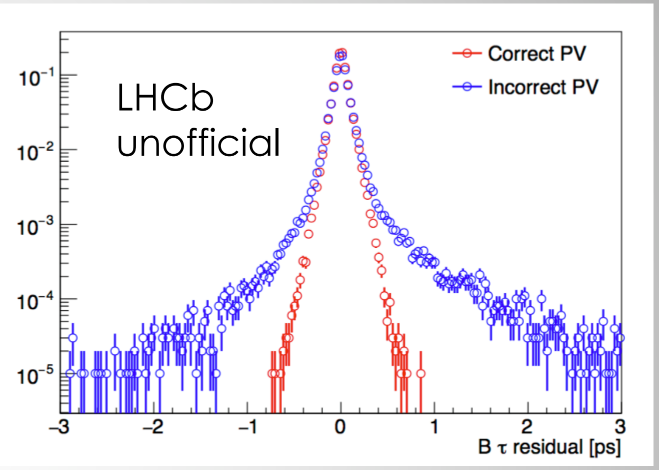
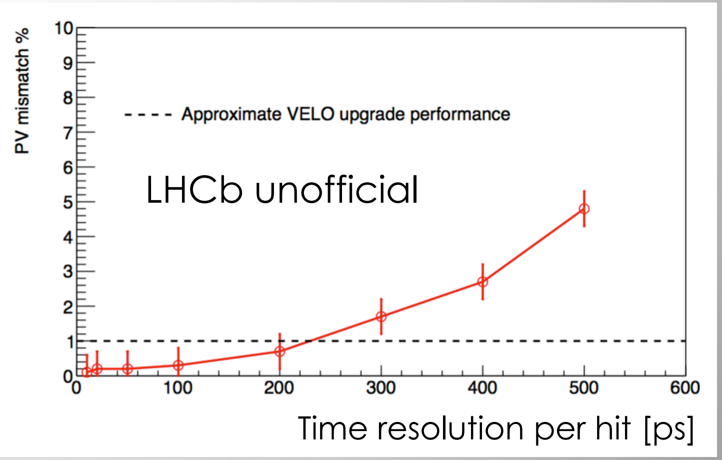
# VELO Phase-II upgrade: Timing & 4D tracking

- Track association to primary vertex
  - VELO upgrade: 1% mis-association
  - At 10x luminosity: 13% mis-association
    - Degrades decay time & IP resolution
- 4D tracking: time stamp each track
  - Improves tracking performance
  - PV mis-association vs. time resolution
    - 200 ps resolution/hit recovers current performance
- Fits well other Phase-II upgrade plans
  - Timing in PID detectors (TORCH)
    - R&D well advanced, option for Phase-Ib
  - Timing in calorimetry
    - R&D ongoing but very expensive



# Summary

- LHCb is a precision experiment in a challenging environment
  - The excellent performance of VELO is crucial for its success
- LHCb Upgrade is read out at 40 MHz @ 5x current luminosity
  - VELO tracking performance is improved
  - VELO resolution is improved or maintained
- Preliminary studies for a Phase-II upgrade
  - 10x upgrade luminosity
  - Challenging but exciting detector R&D prospects